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NON-LOCALIZED IMPACT IONIZATION IN SEMI-CONDUCTORS.(U)
FEB 79 C R CROWELL, C KAO DAHC04-75-G-0002

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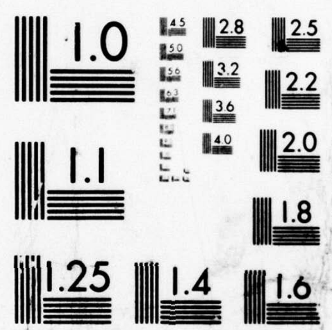

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Studies have been directed towards improving the understanding of the "nonlocalized" nature of impact ionization:. i.e., the fact that carriers must be field accelerated by at least the threshold energy for impact ionization before they can create an electron-hole pair. Work has been directed specifically towards GaAs and InP in Schottky barrier configurations. For GaAs, studies have shown that momentum and energy conservation impose an effective density of available states that grows as the 2 1/2 power of the energy in excess of threshold as opposed to the 3 1/2 and →

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20. ABSTRACT CONTINUED

~~and~~ 5 power alternatives, ~~proposed by Drummond and Moll.~~ It has also been that the capture cross sections that we can deduce from cascade production by high energy primary radiation are consistent with the modeling needed for the ionization coefficient. This problem was investigated using a Markov formulation and the results of the energy required per pair produced are strongly influenced by the ratio of pair production cross section to phonon scattering cross section at a primary energy of twice the threshold energy. The energy dependence about this energy serves mainly to perturb the result. In this work thresholds derived from band structure considerations by Anderson and Crowell were used. The work also puts the experiments in hot electron emission from Si p-n junctions by Bartelink, Moll and Meyer in a perspective that is consistent with the cascade and avalanche measurements.

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"Normalized Theory of Impact Ionization and Velocity Saturation in Non-Polar Semiconductors via a Markov Chain Approach" R. Chwang, C-W. Kao and C. R. Crowell - accepted for publication in Solid State Electronics but presently undergoing revision.

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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

C. R. Crowell

R. Chwang - Ph.D. Thesis, May 1977 "A Markov Matrix Transport Study of Impact Ionization, Velocity Saturation and Cascade Process in Nonpolar Semiconductors".

C-W. Kao

12496EL

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(#7 Continued from P. 1) Attachment

"Photoelectron Injection at Metal-Semiconductor Interfaces", Chung-Whei Kao, C. Lawrence Anderson and C. R. Crowell - invited talk presented at the IVth Conference on the Physics of Compound Semiconductor Interfaces - manuscript in preparation.

"Interrelationship Between Impact Ionization, Velocity Saturation and Cascade Process in Nonpolar Semiconductors" - R. Chwang and C. R. Crowell - talk presented to the International Conference on Hot Electrons, Denton, Texas, July 1977 - Manuscript in preparation.

PROGRESS

The task "Nonlocalized Impact Ionization in Semiconductors" is directed towards improving the understanding of the "nonlocalized" nature of impact ionization: i.e., the fact that carriers must be field accelerated by at least the threshold energy for impact ionization before they can create an electron-hole pair. This concept was first articulated by Okuto and Crowell (O-C) (1) as applied to bulk ionization coefficients, and was used with considerable success to explain the high field ionization rates in Si and low voltage avalanche breakdown in Si and Ge (2).

Earlier O-C stated explicitly an important asymptotic limitation on ionization coefficient imposed by energy conservation (3). Presently reported ionization rates are sufficiently high for GaP (4) (cf. Fig. 1) that they exceed this asymptote and data for holes in GaAs (5) approach this asymptote so sharply that they are subject to considerable doubt.

Our work has been directed specifically towards GaAs and InP in Schottky barrier configurations. This system permits fabrication presumably without structural damage and a better defined field distribution than either an abrupt junction or the collector depletion layer of a transistor. At the same time it is important to determine the field distribution as directly as possible. This has been done by integration of the C-V characteristic when the capacitance is frequency independent (i.e., no deep levels) and the diode is lightly doped. Anderson (6) used this technique for a platinum silicide--silicon Schottky barrier. The C-V measurement system was designed by Anderson, Baron and Crowell (7).

The use of the Schottky barrier permits photoinjection of only majority carriers if a quantum emergy between the band gap and barrier

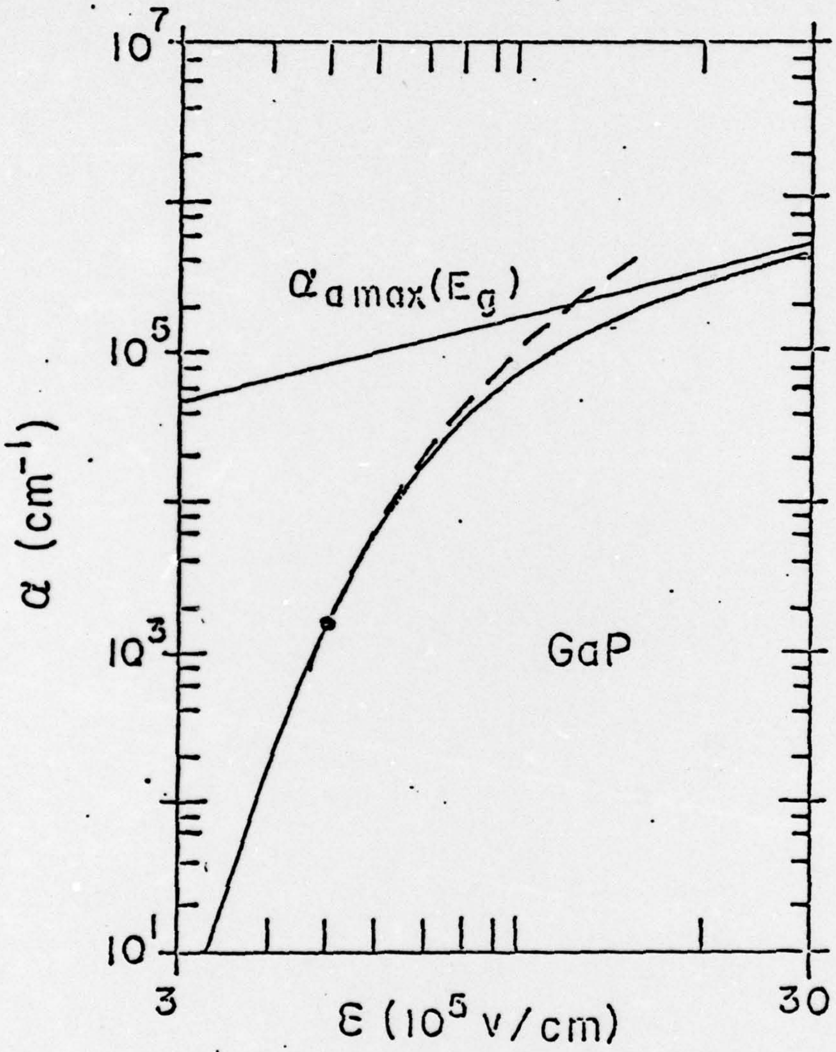

Fig. (1) Ionization coefficient, α, as a function of the electric field, $\mathcal{E}$., for electrons and holes in GaP at 300°K. Legend: ---- experimental(10), —— theoretical prediction obtained by the pseudolocal approximation, o point used to predict the optical phonon scattering mean free path, $\alpha_{a\,max}(E_g)$ ——theoretical maximum α obtained with energy conservation limitation.

height is used. Since the field dependence of the photoinjection process determines the base line from which ionization coefficients are measured, we have made a careful characterization of this process including effects of image force, phonon scattering and quantum-mechanical tunneling in the Platinum-Silicide-Silicon system (8).

We have presently constructed guard ring Schottky barriers in 2×10^{16} cm^{-3} doped n type GaAs with electrolytically grown oxide passivation. The barriers exhibit typical n values of 1.03 and nominal bulk breakdown. Similar diodes in InP are being prepared. Measurement and characterization of the ionization and photoinjection processes will continue into the extension of this program.

To obtain a solidly based characterization of the nonlocalized formulation we investigated the carrier energy distributions implicit in the Baraff modeling (9) and added some refinements - mainly a phonon "darkspace" at low kinetic energies and an energy dependent mean free path for pair production. In our earlier work we had assumed a simple exponential distribution of ionization starting a threshold energy away from the origin of an electron-hole pair. To investigate the validity of this assumption we undertook a Markov matrix formulation of the transport process by dividing the range of the energy distribution into a finite number of states and calculating the phonon and ionization induced transition probabilities (10). Given this fundamental matrix we could follow the spatial distribution of the ionization associated with any initial distribution of carriers. A concurrent calculation of the average velocity in the field direction permitted a calculation of the velocity-field relationship in the high field region near the scatter-limited velocity. The results showed that when parameters deduced from ionization in silicon were used, the field

and temperature dependence were in excellent agreement with the high field measurements by Duh and Moll (11). Satisfactory agreement was also found for electrons and holes in Ge.

In the above formulation, it was relatively straightforward (but far from trivial) to include in the ionization coefficient a calculation of the effect of a finite energy dependence for the ionization cross-section. In so doing we found that we could express the final result for a wide variety of cross-sections simply by substituting the average energy at which ionization occurs for the threshold energy in an analytic function similar to that employed earlier by O-C (3). In addition, we found that except at very high electric fields the effective threshold remains close to the actual threshold energy even when the cross-section for pair production is small. This happens because optical phonon scattering forces most of the energetic carriers to remain near threshold for an appreciable number of scatterings until ionization occurs. This is an important modification of the basic concept earlier assumed, namely that ionization occurs primarily due to a "lucky" electron that reaches the threshold energy. This idea due to Shockley (12) appears in modified form in the assumed trial distribution function used by Baraff and is implicit in Moll's one dimensional (13) formulation of the theory of impact ionization.

Any realistic modeling should include an energy dependence of the ionization crosssection. We have shown that momentum and energy conservation impose an effective density of available states that grows as the 2 1/2 power of the energy in excess of threshold as opposed to the 3 1/2 and 5 power alternatives proposed by Drummond and Moll (14). We have shown as well that the capture cross sections that we can deduce from cascade production by high energy primary radiation are consistent with the modeling needed

for the ionization coefficient. We investigated this problem using a Markov formulation and have shown that the results of the energy required per pair produced are strongly influenced by the ratio of pair production cross section to phonon scattering cross section at a primary energy of twice the threshold energy. The energy dependence about this energy serves mainly to perturb the result (15). In this work we used the thresholds derived from band structure considerations by Anderson and Crowell (16). Our work also puts the experiments in hot electron emission from Si p-n junctions by Bartelink, Moll and Meyer (17) in a perspective that is ocnsistent with the cascade and avalanche measurements.

We have been quite satisfied with our characterization of the injection process for electrons into n type GaAs, but the minority carrier injection appears to have serious difficulties that are probably associated with the material. This is a difficulty that appears to have affected most previous attempts (4, 18) to measure ionization coefficients in GaAs. For this reason we intend to devote an appreciable fraction of future effort to the characterization of our samples of InP.

REFERENCES

1. Y. Okuto and C. R. Crowell, Phys. Rev. B10, 4284 (1974).

2. Y. Okuto and C. R. Crowell, Solid State Electron. 18, 161 (1975).

3. Y. Okuto and C. R. Crowell, Phys. Rev. B6, 3076 (1972).

4. R. A. Logan and H. C. White, J. Appl. Phys. 36, 3945 (1965).

5. G. E. Stillman, C. M. Wolfe, A. G. Foyt, and W. T. Landley, Appl. Phys. Lett. 24, 8 (1974).

6. C. L. Anderson, Ph.D. Thesis, University of Southern California, Los Angeles (1973).

7. C. L. Anderson, R. Baron, and C. R. Crowell, Rev. Sci. Instrum. 47, 1366 (1976).

8. C. W. Kao, C. L. Anderson, and C. R. Crowell, Invited paper presented at the IVth Annual Conference on Physics of Compound Semiconductor Interfaces, Princeton, N.J., February 1977. Abstract in JVST. 14, 937 (1977) - complete manuscript in preparation.

9. G. A. Baraff, Phys. Rev. 128, 2507 (1962).

10. R. Chwang, Chung-Whei Kao and C. R. Crowell, "Normalized Theory of Impact Ionization and Velocity Saturation in Nonpolar Semiconductors via a Markov Chain Approach", submitted to Solid State Electron.

11. C. Y. Duh and J. L. Moll, IEEE Trans. Electron Device ED14, 46 (1976).

12. W. Shockley, Solid State Electron 2, 35 (1961).

13. J. L. Moll and N. Meyer, Solid State Electron. 3, 155 (1961).

14. W. E. Drummond and J. L. Moll, J. Appl. Phys. 42, 5556 (1971).

15. R. Chwang and C. R. Crowell "Interrelationship between Impact Ionization, Velocity Saturation and Cascade Process in Nonpolar Semiconductors" Presented at the International Conference on Hot Electrons in Semiconductors, Denton, Texas, July 1977. Manuscript in preparation.

16. C. L. Anderson and C. R. Crowell, Phys. Rev. B5, 2267 (1972).

17. D. J. Bartelink, J. L. Moll, and N. I. Meyer, Phys. Rev. 130, 972 (1963).

18. H. D. Law and C. A. Lee, Solid State Electron. Vol. 21, 331 (1978).

RONALD JEN-CHUAN CHWANG

DISSERTATION

A MARKOV MATRIX TRANSPORT STUDY OF IMPACT IONIZATION, VELOCITY SATURATION AND CASCADE PROCESS IN NONPOLAR SEMICONDUCTORS

The interrelationship between impact ionization by field accelerated carriers, high field carrier velocity saturation and cascade pair production by high energy carriers in nonpolar semiconductors is investigated. The treatment uses the Markov property of isotropic optical phonon scattering and is formulated in terms of a transition matrix in a discretized energy space. The matrix is a basic kernel for studying the impact ionization probability, transport velocity and energy distribution of charge carriers at very high electric fields at a given lattice temperature. This method avoids any *a priori* assumptions concerning the distribution function and provides better resolution and simulation flexibility than the Monte Carlo approach. Effects of the energy dependence of impact ionization cross-section were studied. Allowing both energy and momentum conservation, the impact ionization cross-section near the threshold, E_{TH}, is proportional to $(E - E_{TH} - E_Q)^{2.5}$ where E_Q represents a restriction due to momentum conservation and is inversely proportional to a combination of the effective mass components of the secondary carriers.

The transport velocity is mainly characterized by isotropic scattering, an energy independent mean free path, λ_p, for nonpolar optical phonon scattering and is nearly independent of the ionization cross-section. The predictions show excellent agreement with high field measurements on n-Si by Duh and Moll. At a lower field the calculations also agree favorably with existing saturation drift velocity data in n and p type Si and p-Ge. The carrier energy distribution is strongly influenced by the ionization cross-section and deviates from Maxwellian at very high fields. The calculated impact ionization probability clearly demonstrates the nonlocalized carrier generation predicted by Okuto and Crowell and provides the exact spatial distribution for a precise treatment to relate ionization coefficients to charge multiplication data at very high fields. In terms of the earlier Baraff model, the effective ionization threshold, $\langle E_I \rangle$, is the average energy at which ionization occurs and is a good physical parameter to describe ionization coefficients which naturally satisfy the energy conservation limit at high fields. An "universal" analytical expression with meaningful asymptotic results for the normalized ionization coefficients is derived.

For the cascade process due to high energy carriers, the ratio of impact ionization to optical phonon scattering probability can be characterized in a stylized form of $C(E/E_{TH} - 1)^d$. We derive recurrence relationships for the eventual ionization probability and the average phonon energy loss before ionization for a carrier with initial energy E. A Markov matrix simulation based on the available density of states function for the secondary carriers provides a fitting for ϵ, the average energy per pair produced. The deduced ionization cross-section in Si based on separate thresholds for electrons (1.1 eV) and holes (1.8 eV) is described by $C = 0.035$ for $d = 2.5$. The effective ionization threshold at low field, ξ, has an upper bound of $E_{TH} + (d + 1)q\xi\lambda_p$ due to the strong coupling for optical phonon emission near E_{TH}. A minor correction to the low field ionization rate is due to the additional number of phonon scatterings required above E_{TH} before ionization. $\langle E_I \rangle$, however, is strongly field dependent at high fields and prevents a constant $\langle E_I \rangle$ characterization of the ionization rate over a wide range of fields. Our results also show a consistent semi-quantitative interpretation for the avalanche energy distribution of hot electrons observed from shallow p-n junctions by Bartelink, Moll and Meyer. This study provides important guidelines for future investigation and a comprehensive picture for characterization of high field avalanche transport and the high energy cascade process of carriers in nonpolar semiconductors.

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NORMALIZED THEORY OF IMPACT IONIZATION AND VELOCITY SATURATION IN NONPOLAR SEMICONDUCTORS VIA A MARKOV CHAIN APPROACH *

BY

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ABSTRACT

This paper presents an investigation of the velocity, energy, and impact ionization distributions in nonpolar semiconductors at very high fields. The treatment uses a finite Markov chain formulation. When optical phonon collisions and impact ionization are the major scattering mechanisms in the semiconductor, a transition matrix which characterizes the transition probabilities between virtual states defined by small discrete energy intervals can be easily computed. The resulting matrix provides the means not only to study the impact ionization phenomenon but also the steady state transport velocity and energy distribution of the charge carriers at high electrical fields and a given lattice temperature. In addition, the effects on the transport properties due to either an abrupt infinite (AI) or a finite energy dependent (FED) ionization cross-section above the ionization threshold energy are examined. The calculated avalanche transport velocity shows excellent agreement with the experimental data in Si obtained by Duh and Moll. The resulting calculations when extrapolated to a lower field also agree favorably with existing saturation drift velocity data in n and p type Si and p type Ge. The energy distribution is shown to be strongly affected by the choice of the model for the energy dependence of the ionization

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cross-section. One of the main applications of the results is to assist investigation of the non-localized nature of electron and hole avalanche ionization coefficients previously noted by Okuto and Crowell (O-C). The present results for this spatial distribution can replace O-C's intuitively chosen exponential approximation. The spatial ionization distribution generated by the present calculation is essentially exponential with a threshold energy dark space. This result provides a useful kernel for a more precise formulation in studies that relate impact ionization coefficients to charge multiplication data. The normalized ionization coefficients obtained from the AI model are very similar to Baraff's calculation as are the FED model results after appropriate normalization. Simple analytical expressions with meaningful asymptotic results for the average ionization energy and the ionization coefficient are also derived from the present data. These results are applicable for a range of different energy dependence of the ionization cross-section provided that the average energy for pair production is used as the effective threshold parameter.